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LOAD RATIO DEPENDENCE OF FATIGUE THRESHOLD IN AERMET 100 STEEL

by

Eun U. Lee

2 October 1996

Aerospace Materials Division
Air Vehicle and Crew Systems Technology Department
Naval Air Warfare Center Aircraft Division
Patuxent River, Maryland

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ABSTRACT

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ACKNOWLEDGMENT

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CONTENTS

SUMMARY

The fatigue crack growth (FCG) behavior of AerMet 100 steel was investigated at various load ratios, ranging from 0.05 to 0.9, in gaseous dry nitrogen. The results of this investigation can be summarized as follows.

Raising the load ratio increases the near-threshold FCG rate below 10^{-5} mm/cycle and reduces the threshold stress intensity range, ΔK_{th}. However, such an effect of load ratio on FCG rate is little above 10^{-5} mm/cycle. ΔK_{th} decreases with increasing load ratio up to the critical value, R_{cr} = 0.5, and levels off above the R_{cr}. With an increase in load ratio, the maximum stress intensity at threshold, K_{max}, increases little from its critical value at load ratio 0. However, it increases rapidly above the R_{cr}. The critical threshold stress intensity range, ΔK^*_{th}, is 2.22 Mpa$\sqrt{m}$ and the critical maximum stress intensity at threshold, K^*_{max}, 3.42 MPa$\sqrt{m}$. The FCG behavior of AerMet 100 steel changes from Class-IIb to Class-IIa with increasing da/dN in dry gaseous nitrogen. The resistance of AerMet 100 steel to threshold fatigue crack growth is determined to be similar to that of 4340 and 300M steels.

INTRODUCTION

Advanced aircraft landing gear and other components demand strong and tough materials to achieve higher performance and greater reliability. In the past, 300M and AF1410 steels were accepted as the materials for aircraft landing gear because of the high strength (300M) and the great fracture toughness (AF1410). Recently, a new Co-Ni alloy steel, strengthened with carbon, chromium, and molybdenum, AerMet 100, was developed. This steel has an outstanding combination of high ultimate tensile strength (UTS), 1,930 - 2,070 MPa, and high fracture toughness, K_{IC}, exceeding 120 MPa$\sqrt{m}$. The UTS and K_{IC} are similar to and much greater than those of 300M steel, 2,000 MPa and 65 MPa$\sqrt{m}$, respectively. On the one hand, they are greater and less than those of AF1410 steel, 1,585-1,724 MPa and 165 MPa$\sqrt{m}$, respectively. Therefore, AerMet 100 steel can replace 300M steel to increase damage tolerance and AF1410 steel to achieve weight reduction. This suggests that AerMet 100 steel has a great potential for application to fracture resistant components, including aircraft landing gear. However, the FCG behavior of this steel was not fully understood.

The objective of this study was to investigate the FCG behavior of AerMet 100 steel, with special emphasis on near-threshold crack growth at different load ratios. A series of fatigue tests were conducted with a frequency of 10 Hz at various load ratios, ranging from 0.05 to 0.9, in gaseous dry nitrogen environment, employing C-R oriented specimens of AerMet 100 steel.

EXPERIMENTAL PROCEDURE

The specimen material, an AerMet 100 steel forging, was supplied by Carpenter Technology Corp. in the form of a 108 mm diameter round bar. The chemical composition of this steel is given in table 1.

Table 1
CHEMICAL COMPOSITION OF AERMET 100 STEEL BAR

Element	Weight (%)
C	0.23
Mn	0.03
Si	0.03
P	0.003
S	0.0009
Cr	3.03
Ni	11.09
Mo	1.18
Cu	0.01
Co	13.44
Al	0.005
Ti	0.009
Fe	bal

The test specimen, selected for this study, was a C-R oriented compact-tension (C(T)) specimen with a width of 25.4 mm and a thickness of 6.35 mm. Specimen blanks, slightly larger than the finished specimen, were removed from the 108 mm diameter bar forging and subjected to the following heat treatment: solution treatment at 885°C for 1 hr, oil quenching to room temperature, refrigeration in liquid nitrogen for 1 hr, and aging at 482°C for 5 hr. The resultant UTS and yield strength were 1,965 and 1,724 MPa, respectively. The plane strain fracture toughness, K_{IC}, was 126 MPa$\sqrt{m}$. The C(T) specimens were prepared by electro discharge machining to the final dimension.

FCG tests were conducted on a 445 kN closed-loop servo-hydraulic Materials Testing System (MTS) machine, monitored and controlled by a computer. The MTS machine was operated under constant amplitude sine wave loading at a frequency of 10 Hz and load ratios (R = minimum load/maximum load), ranging from 0.05 to 0.9. The loading was carried out in a Plexiglas environmental chamber, which was filled with gaseous dry nitrogen and an enclosed specimen. Oil free gaseous nitrogen was dried to 5% relative humidity by passing through Drierite (CaSO4) prior to entering the environmental chamber. The crack length was continuously monitored by compliance measurement technique. The precision of this crack length measurement technique was typically 0.025 mm. Near-threshold crack growth rates were obtained under decreasing K (load shedding) condition with K-gradient parameter $C = -0.16\ mm^{-1}$.

RESULTS AND DISCUSSION

FATIGUE CRACK GROWTH RATE AND STRESS INTENSITY RANGE

The variation of FCG rate, da/dN, with stress intensity range, ΔK, is shown in figures A-1, A-2, and A-3 for R = 0.05 to 0.9. Raising R increases the near-threshold FCG rate below 10^{-5} mm/cycle and reduces the threshold stress intensity range, ΔK_{th}. However, near and above 10^{-5} mm/cycle, the curves of da/dN versus ΔK tend to converge, indicating diminishing R effect with increasing da/dN. This behavior has also been observed in various steels and other materials by a number of investigators.[1-21] Some investigators attributed this behavior in steels to crack closure, induced by plasticity, oxide, or/and surface roughness.[1-9]

THRESHOLD STRESS INTENSITY RANGE AND MAXIMUM STRESS INTENSITY

The variations of threshold stress intensity range, ΔK_{th}, and maximum stress intensity, $K_{max} = \Delta K_{th}/(1-R)$, with R are shown in figure A-4. ΔK_{th} decreases with increasing R until R reaches a critical value, $R_{cr} = 0.5$. At $R > 0.5$, ΔK_{th} levels off and is relatively constant. As R approaches 1, ΔK_{th} reaches a critical value, $\Delta K^*_{th} = 2.22$ MPa$\sqrt{m}$. With an increase in R, K_{max} increases very little from the critical value at R = 0. The critical value at R = 0 is $K^*_{max} = 3.42$ MPa$\sqrt{m}$. However, above R_{cr}, K_{max} increases steeply with R, maintaining ΔK_{th} constant. The two critical stress intensity parameters ΔK^*_{th} and K^*_{max} are known to be affected by microstructure and environment.[20] The dependence of ΔK_{th} and K_{max} on R can be described in terms of the ΔK^*_{th} and K^*_{max}. For $R < R_{cr}$, $\Delta K_{th} = K^*_{max}(1-R)$ and $K_{max} = K^*_{max}$, and for $R > R_{cr}$, $\Delta K_{th} = \Delta K^*_{th}$ and $K_{max} = \Delta K^*_{th}/(1-R)$ and $R_{cr} = 1-(\Delta K^*_{th}/K^*_{max})$.

Using the ΔK_{th}-R data, the entire FCG behavior may be divided into five different classes, as shown schematically in figure A-5.[21] This classification helps in recognizing the individual fatigue behavior of a different family of materials and understanding the relative roles of the environment on fatigue. Class-V behavior is observable in polymeric materials but seldom in metals. The ΔK_{th} increases with R. Class-I behavior, where ΔK_{th} is independent of R, is seen in aluminum-, nickel-, and titanium-alloys and some steels. This trend pertains to materials that are insensitive to environmental effects, commonly observed in vacuum. In the Class-II behavior, ΔK_{th} versus R extrapolates to an intercept of $\Delta K_{th} > 1$ at R = 1. This behavior is noticeable in pure materials of low strength and high ductility and in some of medium/high strength steels having high fracture toughness.[21,22] The Class-II is subdivided further into Class-IIa and Class IIb. Class-III is a normal fatigue behavior, commonly observed in aluminum alloys and some steels. Here ΔK_{th} versus R curve extrapolates to R = 1 at $\Delta K_{th} = 0$. Class-IV shows the behavior with $\Delta K_{th} < 1$ at R = 1. Class-IV is also subdivided into Class-IVa and Class-IVb. According to this classification, the fatigue behavior of AerMet 100 steel in gaseous dry nitrogen is Class-II.

ΔK_{th} is plotted against K_{max}, determined from $K_{max} = \Delta K_{th}/(1-R)$, for AerMet 100 in figure A-6. Such a plot, called fundamental threshold curve, provides interrelation between the two parameters ΔK_{th} and K_{max} defining regimes, where fatigue crack grows (above the curve) and

where it does not (below the curve).[21] In other words, the curve delineates a boundary where FCG starts for a given K_{max} and indicates the resistance to threshold FCG. The figure A-6 also includes limited data of ΔK_{th} versus K_{max} for 4340[9] and 300M[12] steels. From this figure, AerMet 100, 4340, and 300M steels appear to have similar resistance to threshold fatigue crack growth, though their fracture toughnesses are different. (The K_{IC} values are 120, 53, and 65 MPa$\sqrt{m}$ for AerMet 100, 4340, and 300M steels, respectively.)

The variations of ΔK with R and K_{max} are shown for various FCG rates, ranging from $1x10^{-8}$ to $1x10^{-5}$ mm/cycle, in figures A-7 and A-8, respectively. The ΔK versus R curve has a negative slope with a positive intercept at R = 1, and a plateau is observable in the curve only at lower FCG rates, figure A-7. The curvatures of the ΔK versus K_{max} (or fundamental threshold) curves in figure A-8 are large. The large curvature is characteristic of Class-II behavior and indicative of an interaction between ΔK and K_{max}.[21] Such features signify a transition of FCG behavior from Class-IIb to Class-IIa with increasing da/dN.

CONCLUSIONS

Raising load ratio R increases the near-threshold FCG rate below 10^{-5} mm/cycle and reduces the threshold stress intensity range ΔK_{th} in gaseous dry nitrogen. However, such an effect of R on FCG rate is little above 10^{-5} mm/cycle.

ΔK_{th} decreases with increasing R up to the critical value, $R_{cr} = 0.5$, and then levels off above the R_{cr} in gaseous dry nitrogen. With an increase in R, the threshold maximum stress intensity, K_{max}, increases little from its critical value at R = 0. However, it increases steeply above the R_{cr}. The critical threshold stress intensity range, ΔK^*_{th}, and the critical threshold maximum stress intensity, ΔK^*_{max}, are 2.22 and 3.42 Mpa$\sqrt{m}$, respectively.

The FCG behavior of AerMet 100 steel in gaseous dry nitrogen is Class-II and changes from Class-IIb to Class-IIa with increasing da/dN.

The resistance of AerMet 100 steel to threshold fatigue crack growth is similar to that of 4340 and 300M steels.

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APPENDIX A
FIGURES

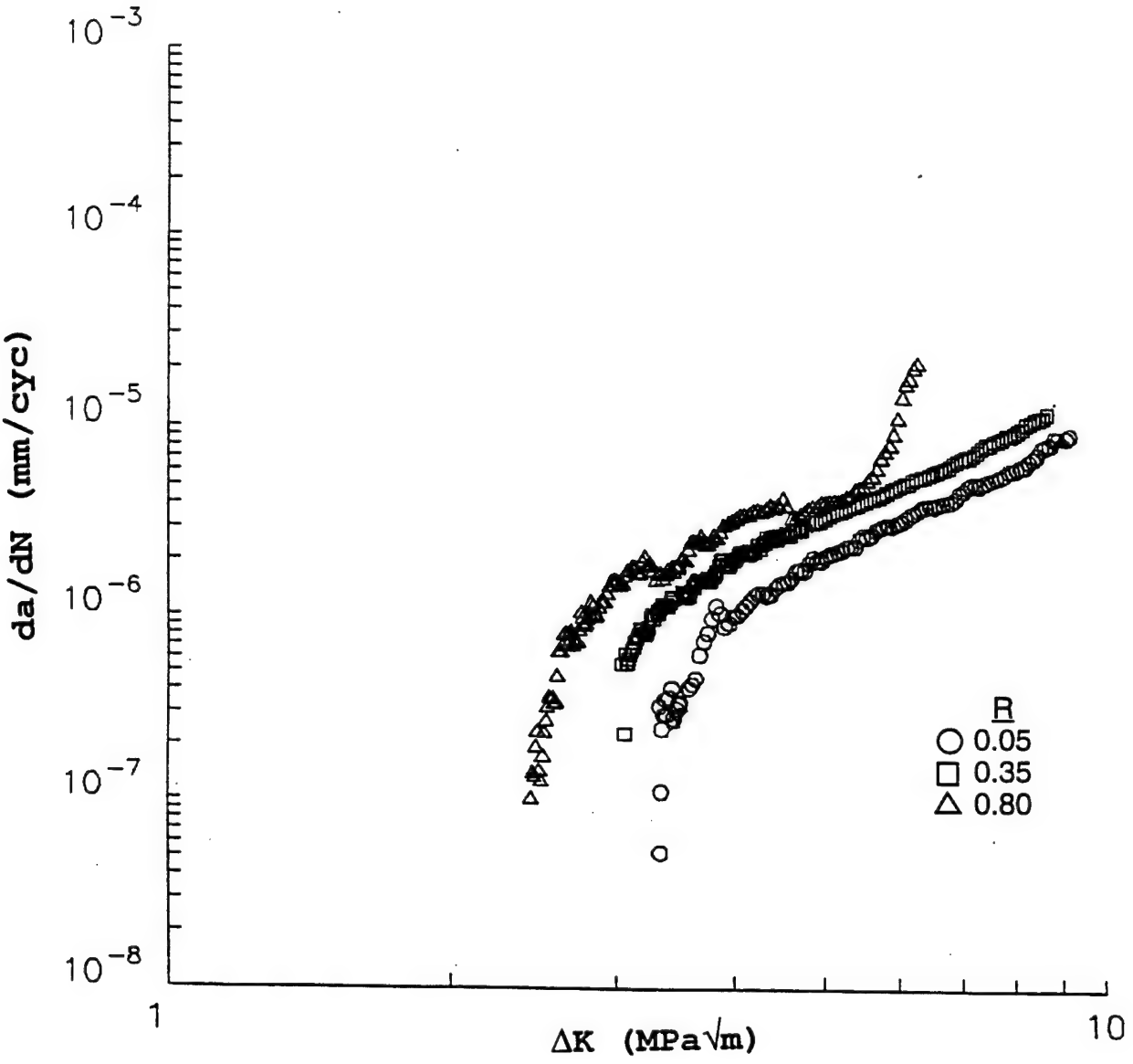

Figure A-1
VARIATION OF FATIGUE CRACK GROWTH RATE, da/dN, WITH
STRESS INTENSITY RANGE, ΔK, AT LOAD RATIO R = 0.05, 0.35, AND 0.8

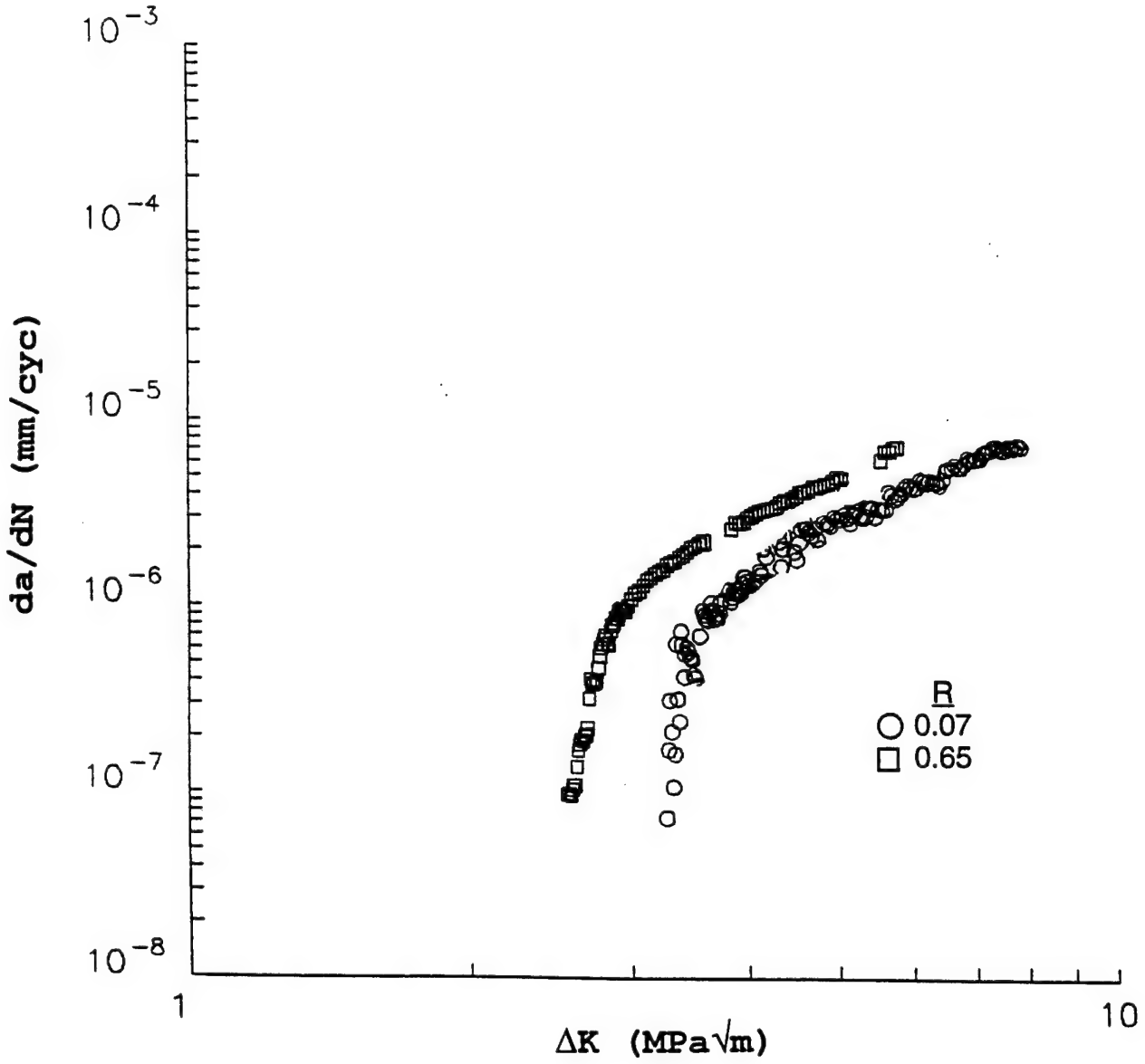

Figure A-2
VARIATION OF FATIGUE CRACK GROWTH RATE, da/dN, WITH STRESS INTENSITY RANGE, ΔK, AT LOAD RATIO R = 0.07 AND 0.65

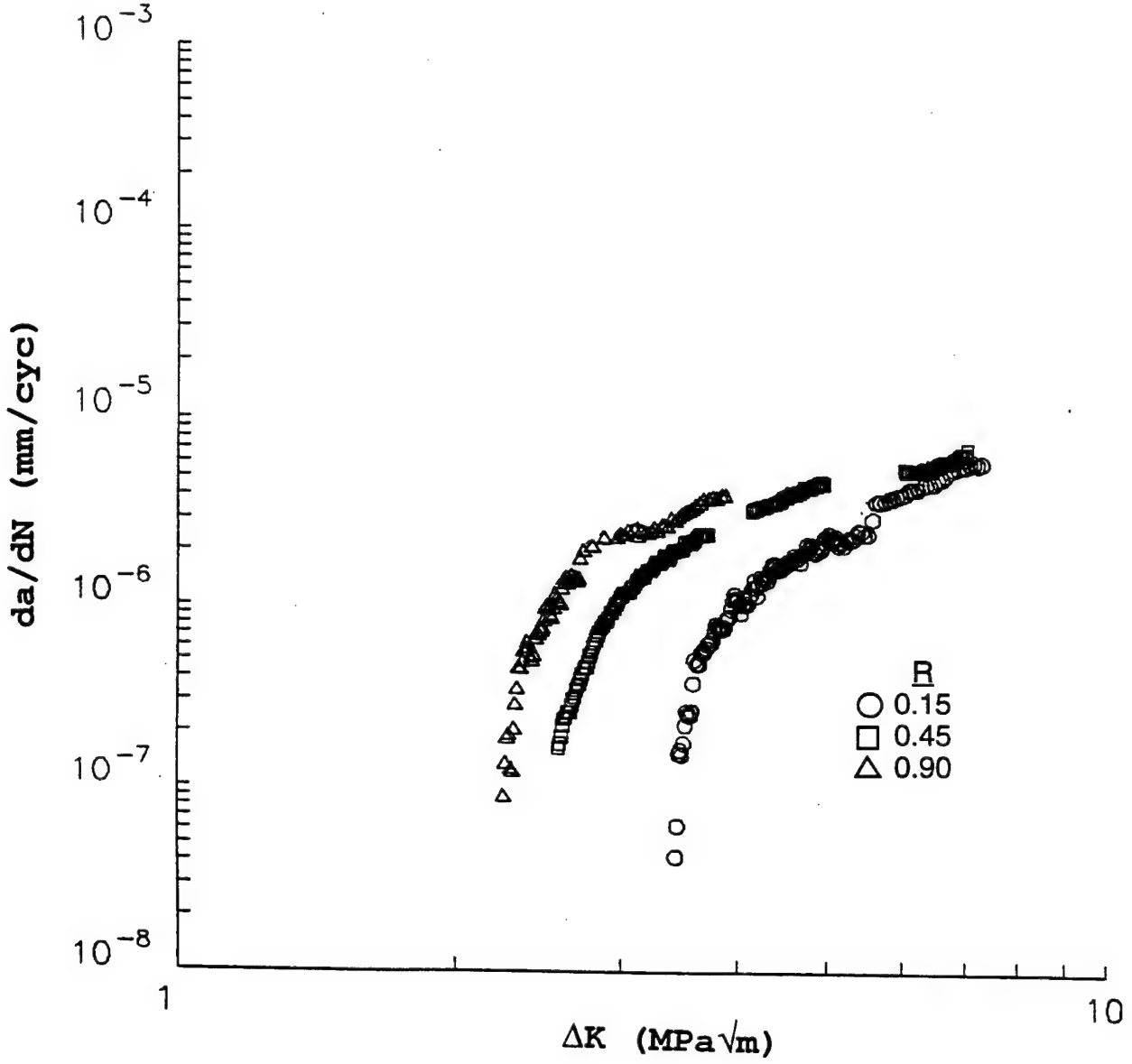

Figure A-3
VARIATION OF FATIGUE CRACK GROWTH RATE, da/dN, WITH
STRESS INTENSITY RANGE, ΔK, AT LOAD RATIO R= 0.15, 0.45, AND 0.9

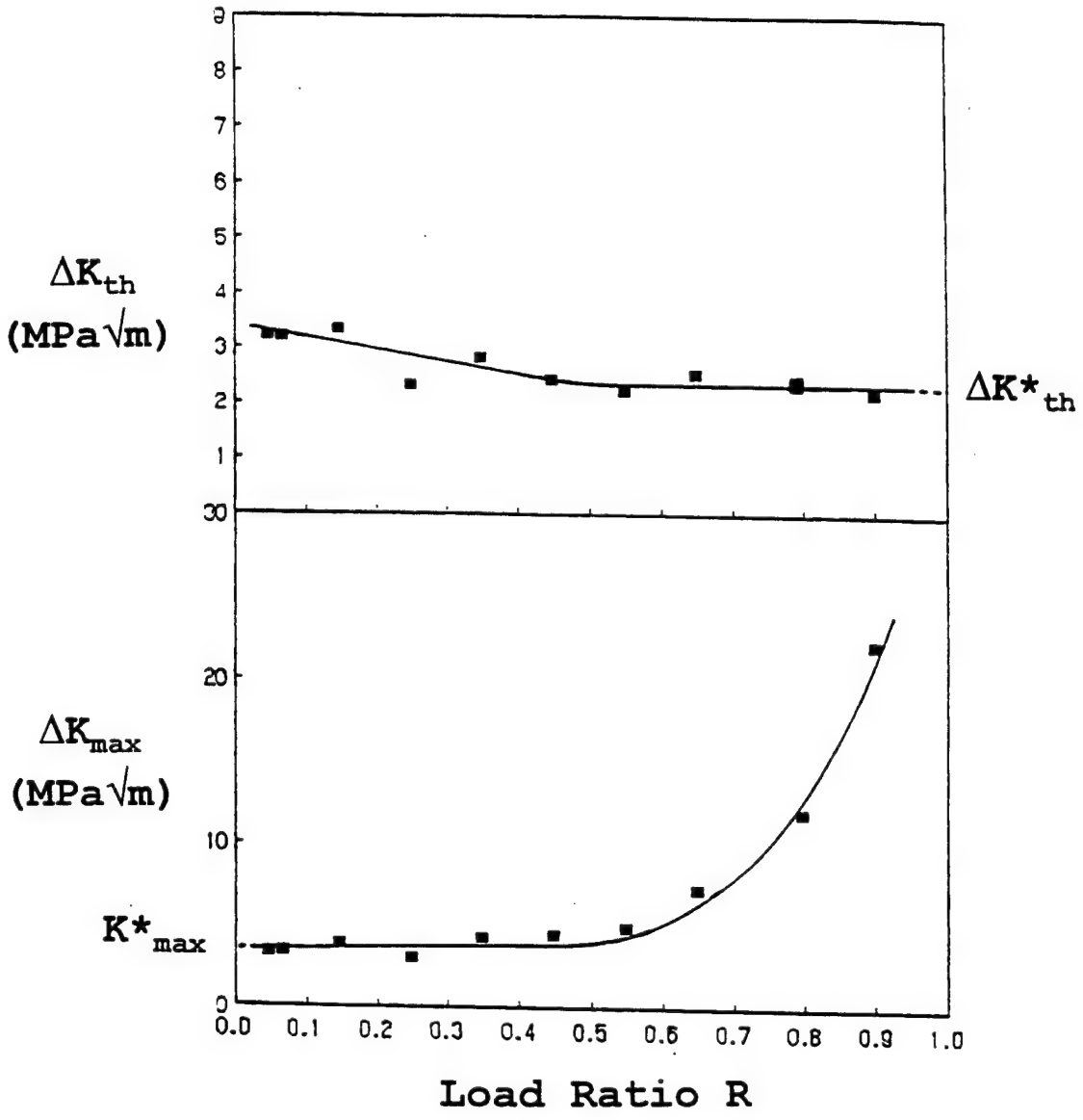

Figure A-4
VARIATION OF ALTERNATING AND MAXIMUM STRESS INTENSITIES
AT THRESHOLD, ΔK_{th} AND K_{max}, WITH LOAD RATIO R

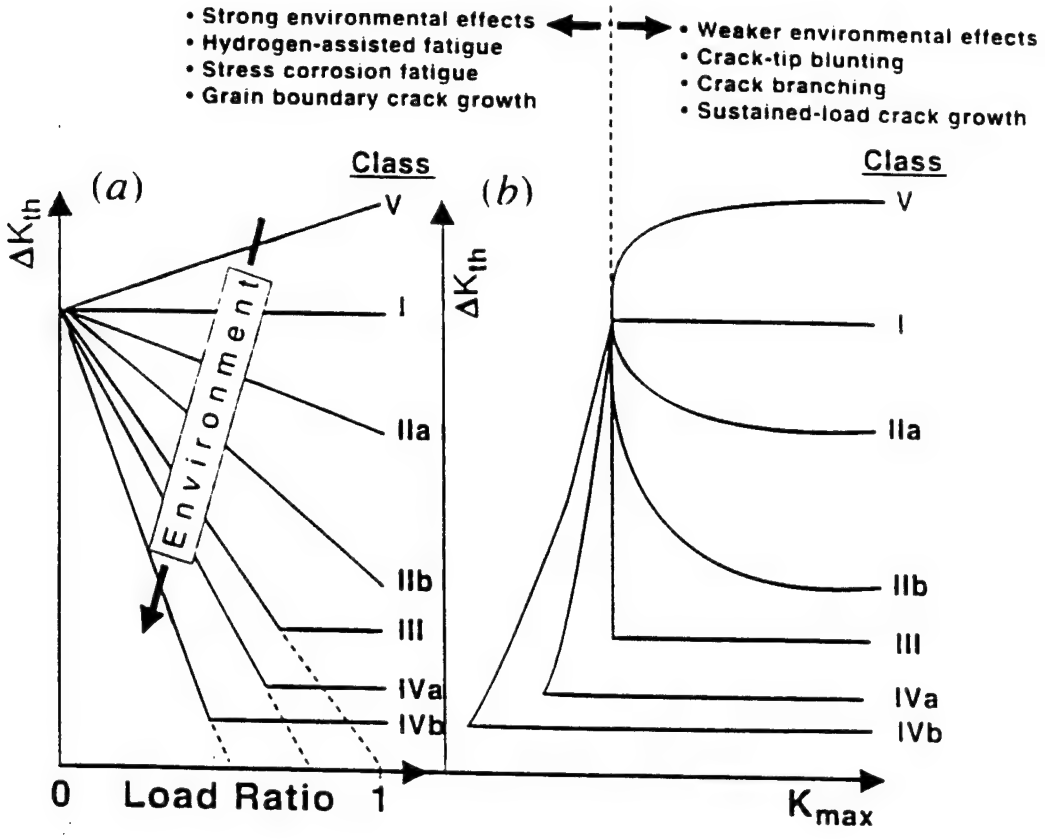

Figure A-5
CLASSIFICATION OF FATIGUE CRACK GROWTH BEHAVIOR[21]

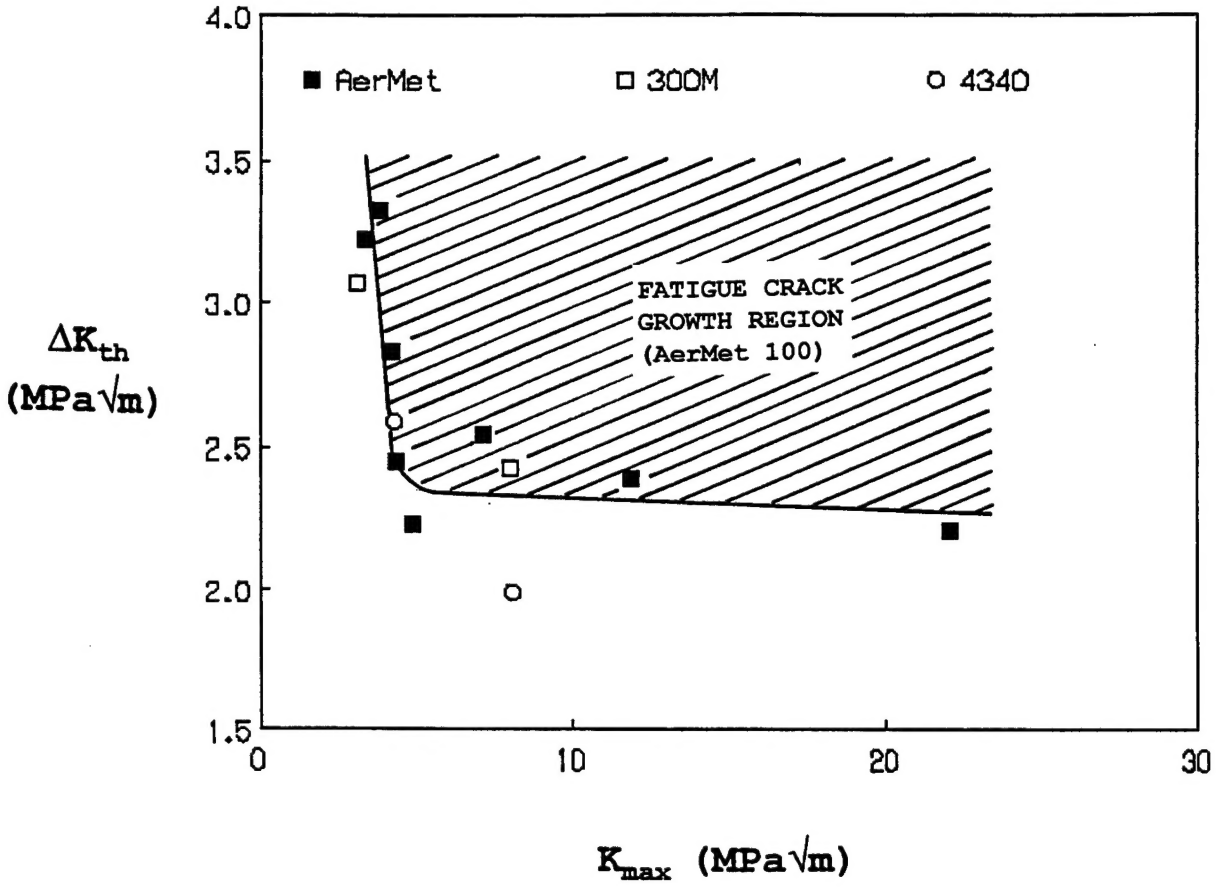

Figure A-6
VARIATION OF ΔK_{th} WITH K_{max}
(Fundamental Threshold Curve)

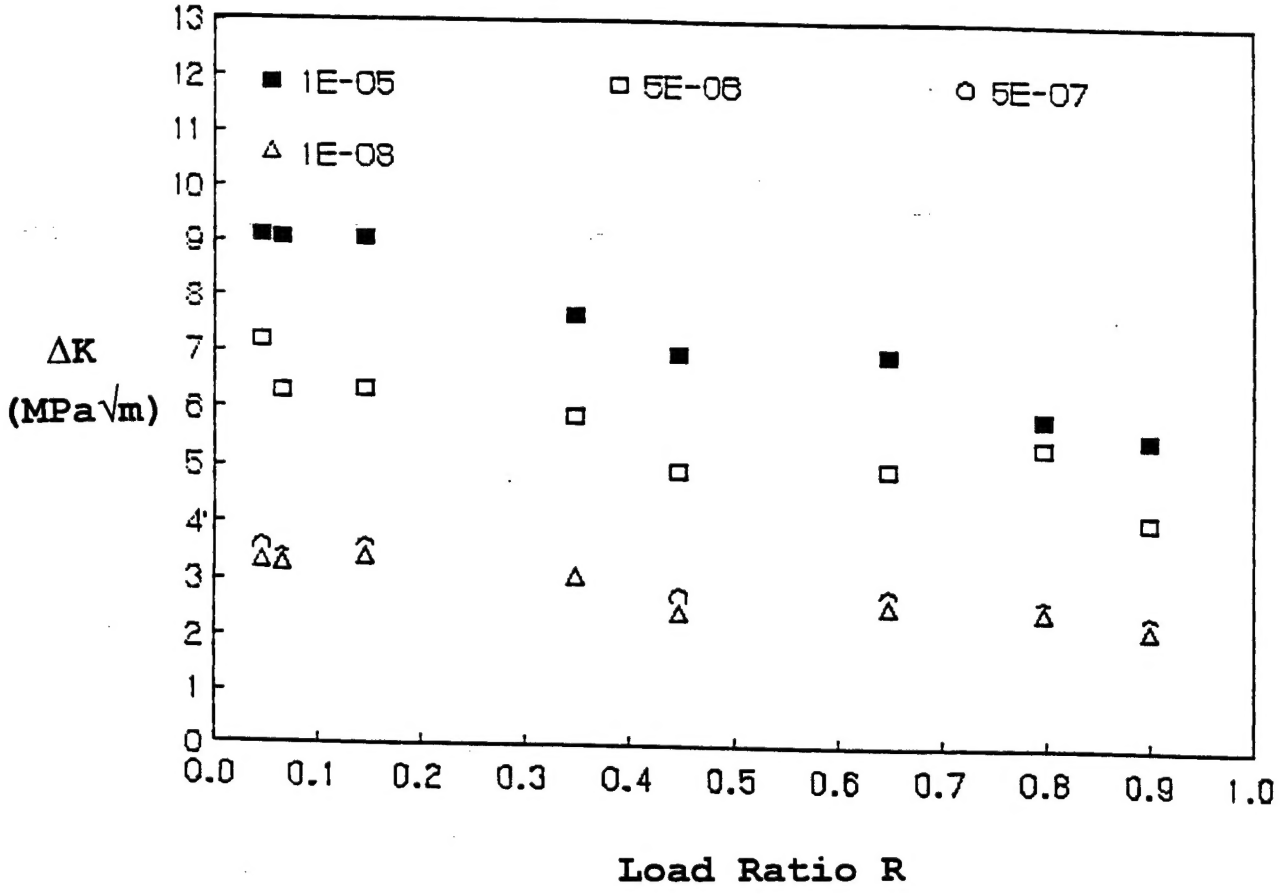

Figure A-7
VARIATION OF ΔK AT VARIOUS da/dN LEVELS VARIATION WITH R

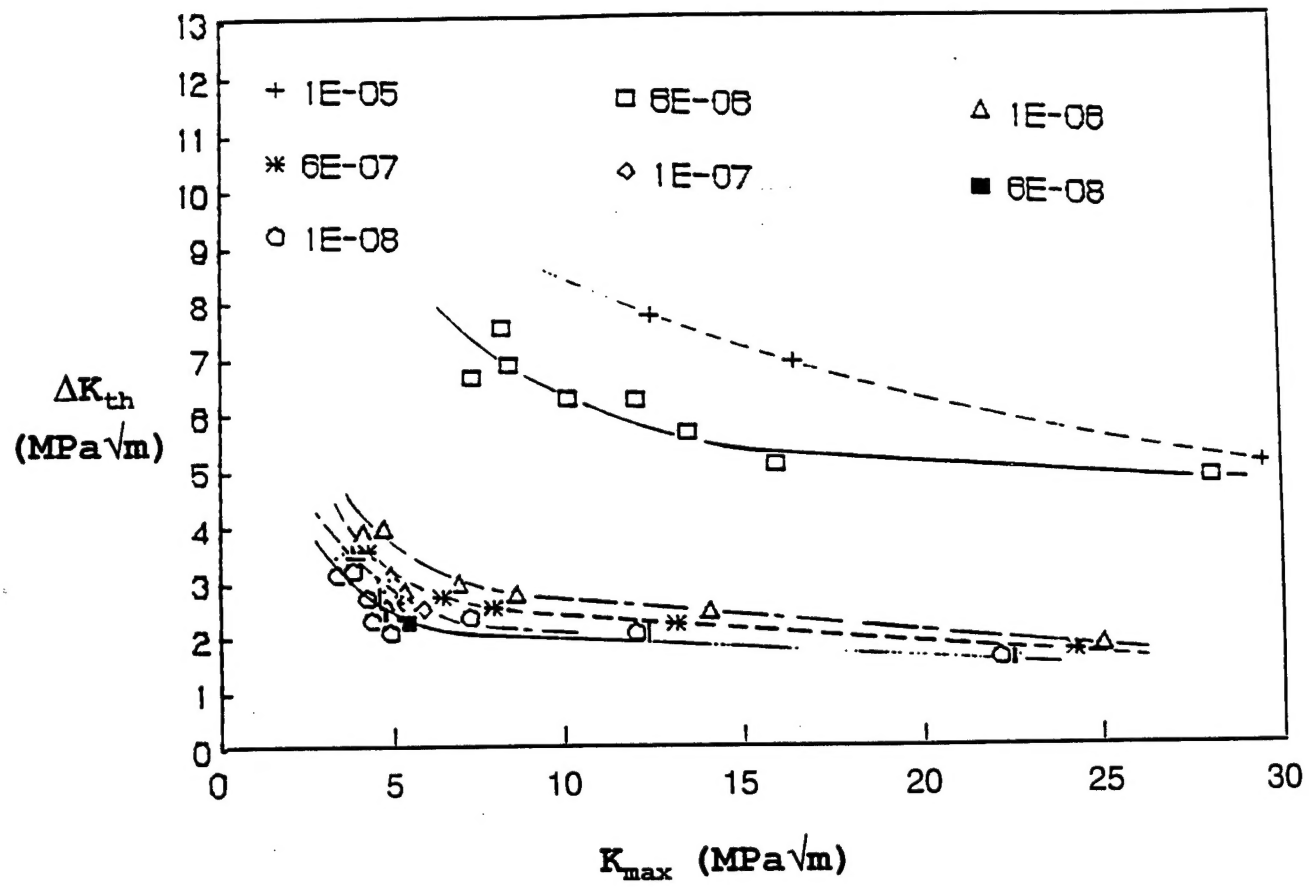

Figure A-8
VARIATION OF ΔK AT VARIOUS da/dN LEVELS VARIATION WITH K_{max}

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